Determining the Motion of the Local Group
Using SN Ia Light Curve Shapes

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ABSTRACT

We have measured our Galaxy's motion relative to distant galaxies in which type Ia supernovae (SN Ia) have been observed. The effective recession velocity of this sample is 7000 km s^{-1}, which approaches the depth of the survey of brightest cluster galaxies by Lauer and Postman (1994). We use the Light Curve Shape (LCS) method for deriving distances to SN Ia, providing relative distance estimates to individual supernovae with a precision of $\sim 5\%$ (Riess, Press, & Kirshner 1995). Analyzing the distribution on the sky of velocity residuals from a pure Hubble flow for 13 recent SN Ia drawn primarily from the Calán/Tololo survey (Hamuy 1993a, 1994, 1995a, 1995b, Maza et al. 1994), we find the best solution for the motion of the Local Group in this frame is 600 $\pm$350 km s^{-1} in the direction b=260° l=+54° with a 1 σ error ellipse that measures 90° by 25°. This solution is consistent with the rest frame of the cosmic microwave background (CMB) as determined by the Cosmic Background Explorer (COBE) measurement of the dipole temperature anisotropy (Smoot et al. 1992). It is inconsistent with the velocity observed by Lauer and Postman.

1.   Introduction

The motions of galaxies provide a dynamical measure of the way mass and light are distributed in the Universe. In 1976, Rubin et al (Rubin et al. 1976, Rubin 1977) used giant Sc spiral galaxies as distance indicators to find evidence for a 600 km s^{-1} coherent motion of neighboring galaxies out to 3500-6500 km s^{-1}. Many subsequent attempts to measure motion that departs from smooth expansion combine redshifts with distance measures (Burstein 1990). This approach yields detections of local flows attributed to nearby mass concentrations (Virgo, Hydra-Centaurus, Great Attractor) of substantial scale and amplitude. The most disturbing finding is the absence of convergence to the cosmic microwave background (CMB) frame. Recently, Lauer and Postman (1994) (LP) surveyed brightest cluster galaxies from Abell clusters and inferred that, remarkably, a volume of space out to 8,000-11,000 km s^{-1} is moving at 560 km s^{-1} with respect to the CMB frame. This lack of convergence to the CMB frame is hard to understand in conventional pictures of structure formation (Strauss et al. 1994) and invites investigation by independent methods. This requires a bright distance indicator that is useful out to 10,000 km s^{-1} and which is precise enough to detect velocity residuals of order 600 km s^{-1}.

The narrow luminosity distribution of Type Ia supernovae (SN Ia) suggests they can provide deep and accurate distance estimates, and information in the light curve shape has improved the usefulness of these objects for cosmological measurements (Phillips 1993, Hamuy et al 1995a). We have developed statistical tools to derive distances using distance independent information contained in supernova light curves (Riess, Press, Kirshner 1995 hereinafter RPK). Following Phillips (1993), the method relies on a "training set" of light curves for supernovae in galaxies with accurate relative distance measurements. This determines the correlation between luminosity and light curve shape. When applied to an independent set of 13 distant SN Ia light curves drawn primarily from the Calán/Tololo survey (Hamuy 1993a, 1994, 1995a, 1995b, Maza et al. 1994, Ford et al. 1993, Riess et al. 1995), the Light Curve Shape (LCS) method provides more precise distance estimates than the standard candle assumption, reducing the dispersion around a Hubble line from 0.5 mag to 0.18 mag. The LCS method also predicts individual distance uncertainties: the median distance error for our 13 supernovae is 4%, with the rest of the dispersion accounted for by random and bulk flow velocities. Although our sample is small, the distances of the galaxies hosting the supernovae are relatively large (up to cz=30,000 km s^{-1}), and the LCS distances are precise enough to provide information about the velocity residuals from a pure Hubble flow.

2.   Measuring the Local Group Motion with SN Ia's

We fit a Hubble line to 13 supernovae (analyzed using LCS, see table 1) to determine simultaneously H_0 (which we discuss elesewhere, see RPK) and three Cartesian velocity components of the mean rest frame of the host galaxies with respect to the Local Group. Transformation from heliocentric redshifts to the Local Group rest frame is done by addition of the vector $(-30, 297, -27)$ km s^{-1} in Galactic Cartesian coordinates (de Vaucouleurs et al 1991,Lynden-Bell & Lahav 1988).

For comparing dipole hypotheses, we use a χ^2 statistic which takes into account both distance and velocity departures from the Hubble line. Our individual distance uncertainties come from the LCS method where the errors inferred are found to be statistically sound (RPK). Individual supernovae have motions that are not modeled by a pure Hubble flow plus a motion of the Local Group. That galaxies have random velocities (RV's) has long been recognized in the literature and is evident in the velocity residuals of our sample. Adopting RV anywhere in the range of 275 to 800 km sec^{-1} yields the expected range of χ^2 for 9 degrees of freedom (13 less 3 velocity components and H$_o$), with little sensitivity to the value of RV. We adopt RV=470 km s^{-1} which yields a χ^2 per degree of freedom of 1 and is consistent with 400 $\pm$139 km s^{-1}, derived from the recent pairwise velocity difference estimate from the CFA redshift survey (Marzke et al. 1995).

To assess how our conclusions depend on our distance and velocity error model, we investigated other plausible error models. These consisted of adopting Marzke's value RV=400 km s^{-1} and then adding in quadrature a term proportional to the velocity (distance), σ_*, to represent uncertainty in photometry, absorption, K corrections, or cosmic scatter; $\sigma_\mu^2 = \sigma_{LCS}^2 + \sigma_*^2$. The largest amount of uncertainty one can add and still maintain a significant χ^2 is 7% of the velocity (σ_*=.15 mag), and even this has little effect on the conclusions we draw.

Minimizing χ^2 with respect to the four free parameters determines the best values: $H_0 = 66$ km s^{-1} Mpc^{-1}, $V_x = -90$ km s^{-1} , $V_y = -510$ km s^{-1} and $V_z = 710$ km s^{-1} . Our calibration of the SN Ia peak magnitude, derived from the HST Cepheid distance to SN 1972E (RPK, Sandage et al. 1994), affects only our estimate of H_0 and not the velocity components. The weighted mean recession velocity of our sample is 7,000 km s^{-1}. To visualize the dipole present in our sample, Figure 1 plots the residual recession velocity from the best Hubble fit (in the velocity rest frame of the Local Group) versus the location on the sky for each supernova. The systematic pattern of residuals which is evident in this figure clearly shows our motion with respect to these galaxies.

Joint confidence regions for the four fitted parameters at various confidence levels

can be determined, in the standard way (Avni 1976, Press et al. 1992), as ellipsoids whose boundaries correspond to specified values for $\Delta\chi^2$. In this case, we determine joint confidence regions for the three velocity parameters V_x, V_y, V_z, with the fourth parameter (H_0) chosen to minimize χ^2 for each value of (V_x, V_y, V_z). With three degrees of freedom in the resulting joint confidence region, the boundary of the 68% confidence region lies at $\Delta\chi^2 = 3.5$, the 95% confidence region lies at $\Delta\chi^2 = 8.0$, and the boundary of the 99% confidence region lies at $\Delta\chi^2 = 11.3$.

We can now ask where the COBE rest frame, and the LP rest frame, lie with respect to these confidence regions:

When the COBE frame $(10, -542, 300)$ km s^{-1} is used $\chi^2 = 12.5$ (D.F.=9), so $\Delta\chi^2 = 3.5$. This is not only inside the 95% confidence region, it is inside the 68% confidence region, showing that our measurement of the Local Group motion is highly consistent with the COBE dipole. For the LP frame $(-470, -399, -333)$ km s^{-1}, $\chi^2 = 32.7$ (D.F.=9), so $\Delta\chi^2 = 23.7$. This lies outside the 99% confidence region. In fact, it is ruled out at greater than the 99.99% ("greater than 3-sigma") confidence level, i.e. there is less than a 1 in 10,000 chance that our result is an unusual data sample from the LP rest frame. We can also determine our consistency with the LP measurement as well as the LP rest frame by adding our errors in quadrature with theirs and evaluating the confidence level with which we can say the difference between the two measurements is zero. Including the errors of both measurements yields a reduced rejection level of 99.45%. Alternatively, we find that the most likely dipole vector for our measurement and the LP measurement taken jointly is $(-340, -420, 140)$ with a joint likelihood of 0.7% or a mutual rejection of 99.3%. Additionally, we have compared our measurement with the IRAS dipole, deduced by peculiar accelerations, and found a high level of consistency ($\Delta\chi^2 = 1.2$, Rowan-Robinson et al 1990). Finally, we can reject the null hypothesis, i.e. no net motion with respect to the supernova frame, at the 99% confidence level.

Our ability to exclude the LP rest frame at interesting confidence levels derives from the small dispersion of the LCS method, yet the same trend is present at lower precision if the analysis is redone assuming SN Ia's to be identical standard candles with 20% distance uncertainty. The relevant χ^2 values are 13.5 (best fit), 14.5 (COBE), 16.4 (no dipole), and 21.7 (LP). The standard candle frame would be consistent with COBE or zero motion, and inconsistent with LP, but naturally with a lower certainty when using the poorer standard candle assumption. That is because there are real variations in the supernova luminosities which are successfully accounted for by LCS. Previous attempts to use SN Ia as standard candles to measure motions of the Local Group have probably suffered from poor photographic data and contained samples which were too nearby to avoid local flows

(Jergen & Tammann 1993, Miller & Branch 1992).

3. Errors, sample bias, and robustness

The method of $\Delta\chi^2$ intervals also predicts uncertainties on the cartesian velocity components which result in $\mathbf{V} = (-90 \pm 370, -510 \pm 510, 710 \pm 220)$ km s^{-1}. Here the errors are 68% confidence limits on each Cartesian component considered separately (i.e. when χ^2 is minimized with respect to the other components). Because supernovae are discovered at high galactic latitude, our measurement of the motion is better in the z-direction which points out of the galactic plane than in the x and y directions along the galactic plane. The LP frame predicts motion in the z-direction with the opposite sign at $V_z = -333$ km s^{-1}, and this difference accounts for our strong statistical rejection of that motion. If we were to treat our single estimate of the dipole as coming from the distribution defined by our errors, then evaluating the best direction and magnitude of our vector would cause a bias on the best-fit spherical coordinates. For example, we note that the maximum likelihood scalar length of our dipole, 600 km s^{-1}, is smaller than the 880 km s^{-1} which one would naively derive from the Cartesian components (biased to higher values by the uncertainties, see Kendall 1976).

To evaluate the reliability of our uncertainty estimates, we performed a Monte Carlo simulation with 100,000 synthetic data sets of 13 supernovae with the same positions and uncertainties as ours, as displayed in Figure 2. These simulations verify our $\Delta\chi^2$ uncertainty estimates to within 1% and demonstrate our ability to discriminate systematic motions on the basis of 13 accurate distance indicators of wide spatial distribution. Our most likely agreement with COBE is at the 1 sigma level; the most likely rejection of the LP frame is at the 3 sigma level. In recovering our dipole, we find a small geometric bias of $(9, -28, -3)$ km s^{-1} incurred by simultaneously solving for the expansion and the motion of a sample which is not uniformly distributed over the sky.

We also performed a series of jackknife tests to assess the influence of outliers on our results, with the conclusion that our results are robust against deleting any 1 or 2 supernovae from the sample. For example, removing the two farthest supernovae (new effective velocity = 5,900 km sec^{-1}), the two nearest supernovae (new effective velocity = 8,200 km sec^{-1}) or the two supernovae with largest distance uncertainty had no significant effect on any of the results.

Our corrections for galactic absorption (Burstein and Heiles 1984) are small, and omitting these corrections does not alter our result. Host absorption appears insignificant

in our sample. All of the supernovae were discovered far from the centers of their galaxies and none of the spectra of these supernovae showed strong NaI D absorption. Finally, any error incurred by assuming the sample mean host extinction is equal to that of SN 1972E affects only our measurement of H_o, but not the direction of the inferred dipole. Including estimates for individual object deviation from the mean host extinction (up to σ_{A_V}=0.15 mag) does not significantly alter our results.

Finally, we considered the effects of sparse sampling and clustering on our ability to resolve a dipole. Measurement of a dipole in a complex velocity field from a limited number of objects can be distorted by small-scale velocity patterns (Kaiser 1988, Feldman & Watkins, 1994). Uroš Seljak (private communication) has calculated the window function for our sample and convolved it with a standard CDM power spectrum to determine the components of the covariance matrix and thus estimate the dipole components and their uncertainty. This procedure yields a maximum likelihood estimate of $(-42 \pm 445, -517 \pm 575, 716 \pm 276)$ km s^{-1} which is highly consistent with the value and uncertainty we derive for the dipole without considering these effects. Including velocity correlations also yields a greater consistency with the COBE dipole ($\Delta\chi^2 = 2.4$) and a reduced lower bound on the rejection of the LP frame (99.8%) and the LP measurement (98.4%). The latter is a lower bound because the two samples measure some of the same space (e.g. SN 1993ae is in Abell 194) and have some small-scale flows in common. We intend to pursue N-body simulations to see how SNIa can be used to discriminate among cosmological models (Seljak et al. 1995).

4. Interpretation

Our result is consistent with the COBE rest frame, but not with that proposed by LP. Although our effective velocity is 7,000 km s^{-1} and the Abell Cluster inertial frame used by LP is effectively in the range of 8,000-11,000 km s^{-1}, we can easily extend our result up to 8,000 km s^{-1} by excluding two nearby supernovae. In addition, LP have reduced the effective velocity of their sample to 5,000 km s^{-1} by excluding distant clusters. Neither change affects the two derived motions, or brings them into agreement.

The motion of the Local Group relative to the galaxies in our sample is, within the errors, the same as our motion relative to the CMB. The most economical conclusion to draw is that the galaxies at 7,000 km s^{-1} are at rest in the cosmic frame. If this is true, it is possible that the LP measurement may be telling us something about the uniformity of

the galactic luminosity function on large scales. With an enlarged supernova sample, we will attempt to confirm and further constrain these interesting results.

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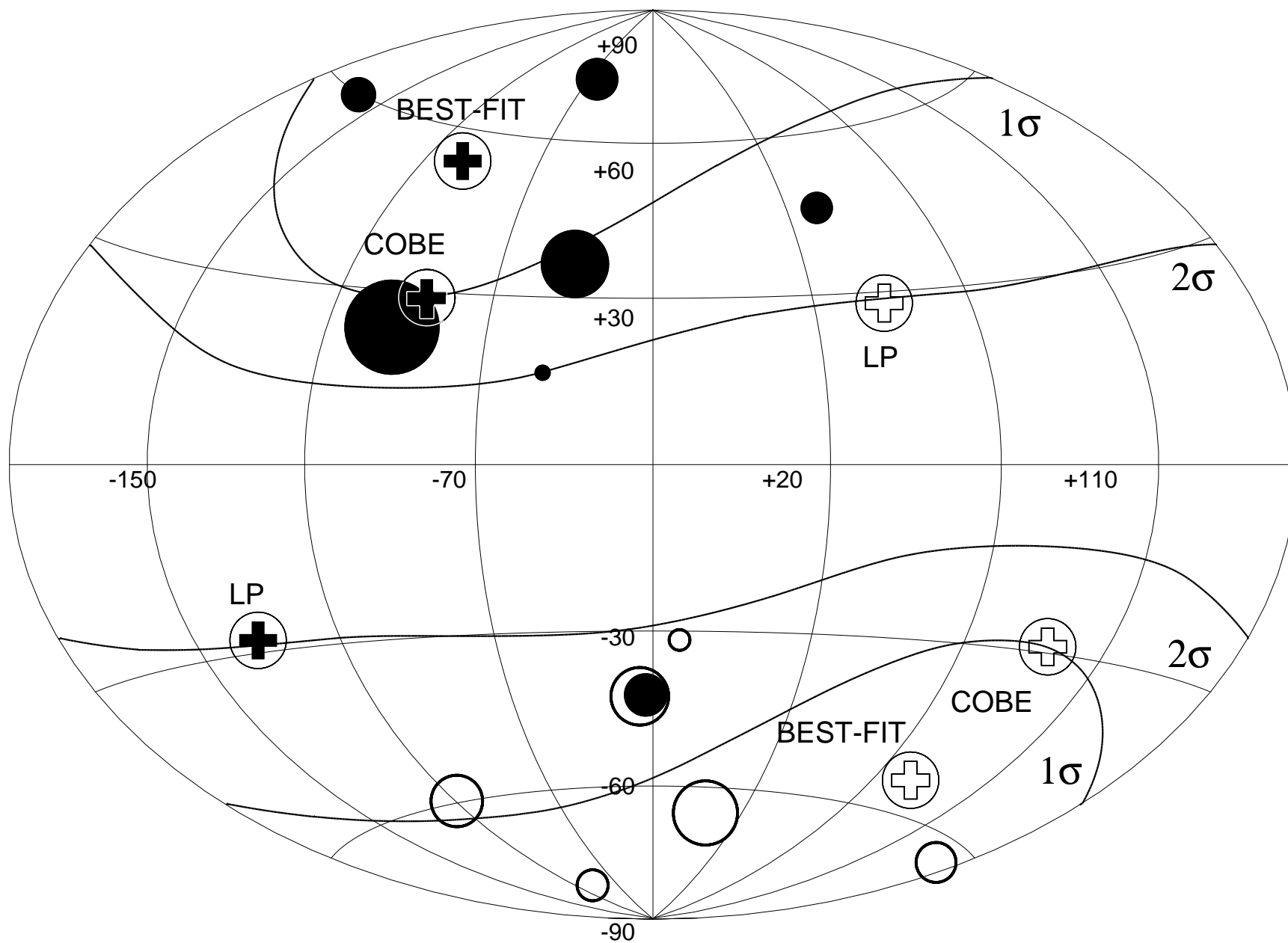
Figure 1: Hubble diagram velocity residuals and predicted Local Group motion on the sky. Filled/Open points represent supernovae with negative/positive residual velocity; the area of the points correspond to the magnitude of the velocity residual. Filled/Open crosses show the direction towards which the Local Group is approaching/receding according to the best fit for the data in this paper, the COBE satellite, and Lauer and Postman's survey of brightest cluster galaxies. One and two sigma contours are displayed for the direction of the best fit to the supernova residual velocities. Coordinates are galactic with the central meridian at $335°$.
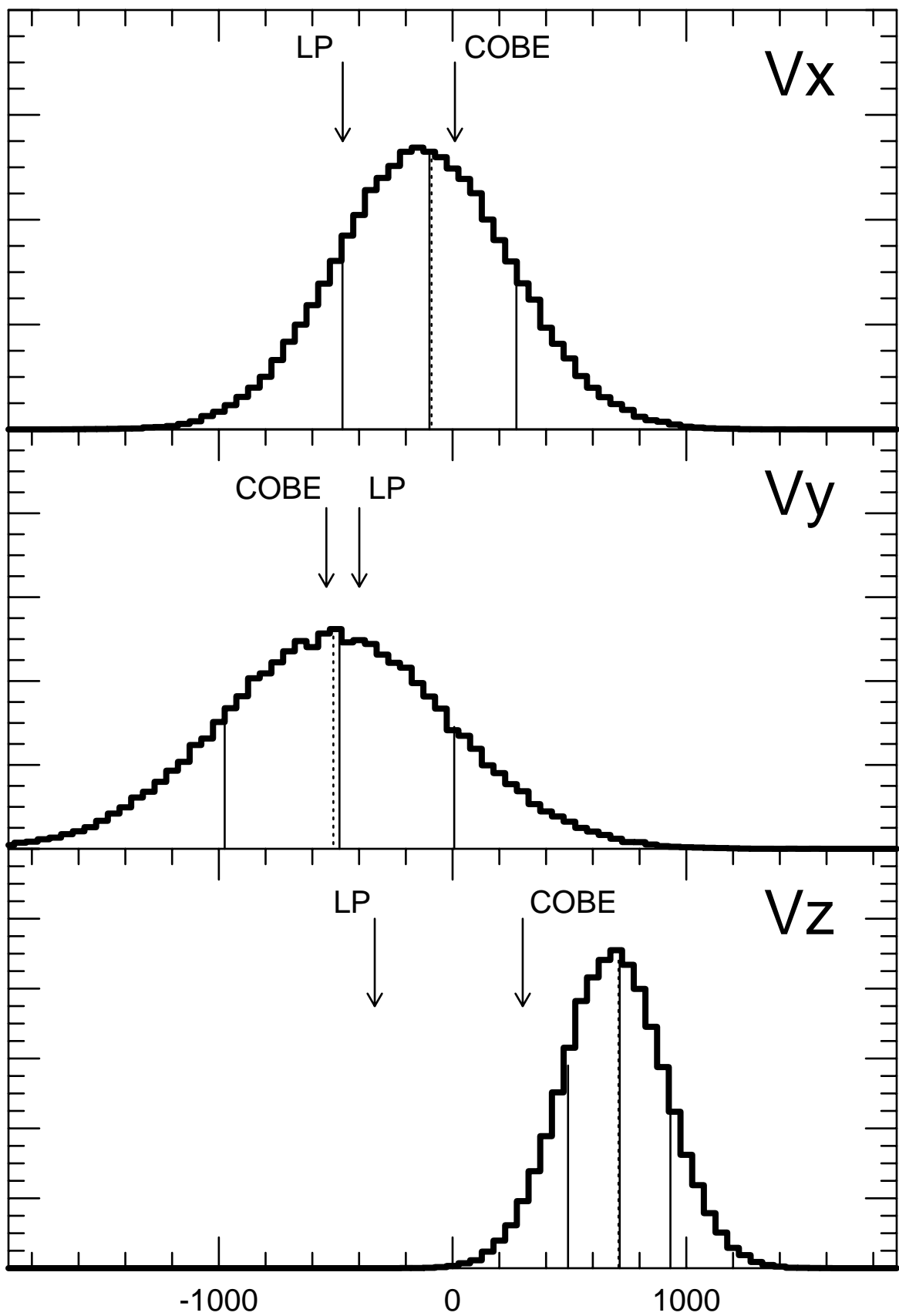
Figure 2: Monte Carlo dipole recovery simulation. 100,000 synthetic data sets of 13 supernovae were created with the same positions and uncertainties as our sample and our adopted dipole motion of $(-90, -510, 710)$ km s^{-1}. These are the distributions of the cartesian components of the dipole recovered from each synthetic data set. The difference between the mean (solid line) and the adopted dipole (dotted line) represents a geometric bias of $(9, -28, -3)$ km s^{-1}. The 1 σ boundaries (outer solid lines) confirm the χ^2 errors to within 1%. The arrows show the COBE and LP measurement of the dipole components. This simulation also verified our most likely agreement with COBE to be at the 1 σ level, the most likely disagreement with LP to be at the 3 σ level. The difference between our result and the LP result is most conspicuous in the z-direction.

Table 1: SN Ia Parameters

Supernova	$\log v(kms^{-1})$	l	b	μ (LCS)*	σ_μ
1992bo	3.753	261.88°	−80.35°	34.53	.08
1992bc	3.782	245.70°	−59.64°	34.48	.08
1992K	3.451	306.28°	16.31°	33.15	.38
1992aq	4.485	1.78°	−65.32°	38.21	.08
1992ae	4.350	332.7°	−41.99°	37.68	.09
1992P	3.872	295.62°	73.11°	35.39	.05
1992J	4.120	263.55°	23.54°	36.88	.13
1991U	3.968	311.82°	36.21°	36.02	.13
1991ag	3.618	342.56°	−31.64°	33.90	.06
1990af	4.178	330.82°	−42.24°	36.62	.06
1992G	3.257	184.62°	59.84°	32.57	.08
1991M	3.396	30.39°	45.90°	33.11	.17
1993ae	3.769	144.62°	−63.23°	34.54	.14

*μ is our distance modulus; σ_μ is the uncertainty; log v from CTIO

velocity (km s^{-1})